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REMOTE OPERATOR PERFORMANCE USING BANDWIDTH LIMITED TV DISPLAYS: A REVIEW AND PROPOSAL

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August 1980

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This report is part of the overall effort to improve remote operator performance in a work and recovery system by optimizing the viewing system. It features (a) a detailed analysis of remote viewing systems and the problems encountered in their assessment; (b) a literature review of the effect of viewing systems limitations on remote vehicle operation, including limited bandwidth, number of cameras and time delay; and (c) a proposed set of experiments to determine the effects on operator performance of three bandwidth compression variables applied either singly or in combination with the operator selecting the levels that maximize performance.

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CONTENTS

INTRODUCTION

This work is part of an effort to develop a deep ocean work and recovery system for the Navy. The objective of this task is specifically directed toward the development of a remote viewing system that will provide the operator with the optimum information to maximize the operation of a remote submersible work vehicle with the capacity for mobility and mechanical manipulation. The approach to developing this viewing system will be to accumulate a definitive body of knowledge that will enable the selection, specification and procurement of a set of system components that will optimize the operator's performance. This will be accomplished through a series of laboratory investigations of the human perceptual requirements for man to operate the submersible.

This report is directed toward improving remote operator performance. The research proposed here was stimulated by past operational experience with several undersea work systems which indicated that existing viewing systems did not provide sufficient information for maximum manipulator operation and vehicle control. The goal is to improve the vehicle operator's performance by utilizing characteristics of human perceptual performance to define the optimum viewing system.

The transmission link determines that available bandwidth for the video display in a remote viewing system. All present indications suggest that the telemetry link for the vehicle system will be coaxial cable with the result that the bandwidth will be limited. This dictates that the vehicle operator's performance be tested to select the optimal set of video information channels within the limits imposed by bandwidth compression techniques.

OBJECTIVES

The immediate objectives of this research effort are (a) to provide a literature review on the effects of viewing systems limitations on remote vehicle operation (including limited bandwidth, limited number of cameras, and time delay); and (b) to define a set of experiments to determine the effects of such bandwidth reduction techniques on remote vehicle operator performance.

The long-range (future) objective of this effort would include the conduct of these experiments in order to determine the effects of a number of bandwidth compression variables singly and in combination, on the operator's performance during typical underwater search, recovery and repair tasks. While this objective seems relatively simple and straightforward, there are a number of complicating factors that make it necessary to adopt a multifaceted approach to its resolution. These factors include the problems of generalizing from laboratory tasks to real life work situations, the main and interactive effects of the perceptual-motor requirements of the task, the several types of learning that result from the repeated

trial designs mandated by our methodologies, the degree to which visual and kinesthetic feedback is present, and the visibility conditions. [See Smith, Cole, Merritt and Pepper (1979) for a detailed account of these problems.]

As a consequence of these complicating factors, evidence bearing on the central research question will require the design of a sequence of studies in which these factors are controlled and which is based on an analysis of the level in the operator's information processing network that is most affected by the various combinations of bandwidth reduction techniques. Therefore, the general organization plan of this paper begins with a detailed analysis of remote viewing systems and the problems encountered in their assessment. It then proceeds with a literature review of the effect of viewing systems limitations on remote vehicle operation, including limited bandwidth, number of cameras and time delay. It concludes with a proposed set of experiments that can be conducted at the NOSC Perception Laboratory to determine the effects of bandwidth compression variables applied to viewing systems on remote vehicle operator performance.

BACKGROUND

Teleoperator Systems

For the purpose of this paper, teleoperators are defined as submersible work vehicles with the capacity for mobility and mechanical manipulation, both of which are controlled by a human operator located on the surface utilizing a remote viewing system and/or other sensors to bring perceptual information from the work site. Of these components, the present focus of interest is on remote viewing systems. Reference to mechanical manipulators is restricted to their potential as sources of perceptual feedback. Detailed presentation of recent advances in teleoperator research and design are found in Sheridan and Verplank (1978) and Bejczy (1980).

Remote Viewing Systems and Their Limitations

The essential features of a remote viewing system are a camera (or cameras) to record and transduce the available energy patterns contained in the image present at the work site, a transmission link to relay the information from the teleoperator to the display site, and a receiver to reconstruct the image received through the transmission process. Any remote viewing system will provide less information than that which is available to a normal observer directly viewing the scene at the work site and will also contain errors and distortions due to the transduction and transmission systems. The amount of information loss and distortion is dependent on the various electro-optical features of the viewing systems and their state of tuning at the time of testing. Because of these limitations, any research assessment of remote viewing systems requires measurement of the information loss/distortion resulting from the viewing system. This can be determined by comparing the operator's performance while directly viewing the task components with that attained using the viewing system. These same limitations also require that performance using the experimental system be compared to a standard viewing system to determine if the experimental condition either degrades or enhances the information presented to the operator. That standard has normally

been a single camera display system whose maximum information transmission is that defined by the United States National Television Systems Committee (NTSC) code for broadcasting, i.e., 525 scanning lines of resolution with a frame rate of 30 f/s and a bandwidth requirement of about 4.5 megahertz.

Given these inherent limitations of remote viewing systems, one major line of research over the years has been devoted to increasing the amount of information displayed and to assessing the effects of the enhanced display on the remote operator's performance. Efforts along this line have included the addition of a second or third camera to supply alternative views of the work scene or two cameras arranged to provide stereoscopic depth information, head-coupled camera movement to provide additional information on the location of objects in space through motion parallax, relative position and other movement-induced information, and color. In addition to their potential for enhancing the viewer display, these features have a common drawback. That is, they place increased demands on the transmission link connecting teleoperator and remote viewing system. The newer digital telemetry systems for a single conductor cable link usually incorporate a technique of time division multiplexing (TDM), where a serial data bit stream is placed on a separate carrier for transmission over the cable. The television signal is one of the hardest to handle in the telemetry system and is usually a forcing function on allowable cable length, diameter, and attenuation, the main reason being the excessive data bit rate imposed by the bandwidth requirements. Basically, the bit rate requirements are given by the product of the horizontal and vertical (pixel) resolution times the dynamic range (gray scale) resolution times the frame rate/sec. Depending on the degree of resolution required, this could typically be in excess of 30 megabits/sec, near the limits of most coaxial cable systems in use today. For this reason, a second major line of research on remote viewing sytems has been directed toward the development and assessment of various bandwidth reduction techniques. A later section of this paper contains a literature review focused on these two areas of research, the one devoted to improving image quality at the display, but which increases bandwidth requirements in the process, and the other which is devoted to reducing bandwidth requirements but which degrades the image in the process.

Problems in Assessing the Effects of Remote Viewing Systems on Operator Performance

As stated previously, remote viewing systems result in both the loss of and distortion of information available to the operator as compared to that available under direct viewing conditions. Performance decrements would normally be expected to occur with either information loss or distortion but in fact, whether a decrement occurs and to what degree depends on the complex interaction of a number of variables, including the following.

Nature of the Teleoperator Task. Task demands include such diverse actions as searching for and recognizing the task site, guiding the vehicle to the task site and to its work position, and inspecting, repairing or retrieving the target. Depending on the nature of the target and the mission, the perceptual and motor requirements on the operator can be vastly different. One approach to the analysis of task features is exemplified by the work of Bertsche, Logan, Pesch and Wernli (1978) who begin by cataloging all of the actions (cutting, drilling, tapping, etc.) that divers have been called on to perform in the past. These are then

broken down into common elements (e.g., rotary motion, linear motion, velocity, etc.) which when taken in various combinations describe the total set of mission tasks. An alternate approach was developed by Pepper and Cole (1978) in designing a research program to assess display systems. They grouped and analyzed tasks based on the common perceptual and motor components required to perform the tasks. Both of these approaches serve to guide the design of the present study.

Sensory Feedback. There are four sources of sensory feedback that are potentially useful for remote manipulator tasks: visual, kinesthetic, tactile and auditory (Holman, 1979).

Vision, as provided by closed circuit TV, is the most important. As will be seen in the literature review, much ongoing research is directed at increasing the visual information available to the operator. Improvements in contrast, resolution, the addition of stereo depth and color show promise of improving performance of both pure perceptual tasks as well as those involving manipulation. Kinesthetic information is the next most important source of sensory feedback and is present to a significant degree where the operation of the manipulator is performed essentially by analogous movements of the operator's arms and hands. Depending on features of the task (e.g., opportunity for learning) and visibility conditions, kinesthetic information can significantly enhance and even replace visually provided information.

Tactile and auditory information are not presently utilized to any great extent, but remain as potential sources of sensory feedback to be developed.

Manipulator Control. The manipulators employed by teleoperators vary on many dimensions that have important consequences for the assessment of remote viewing systems. At the one extreme are position control systems that are controlled by an exoskeletal device worn by the operator that reproduces many of his shoulder, arm and hand movements. When equipped with sufficient degrees of freedom and force feedback, operators can successfully perform intricate tasks with a minimum of concentrated effort. Such a system utilizes our highly developed and integrated perceptual-motor feedback systems that allow us to perform complex operations almost automatically with little guiding thought or calculation. At the other extreme are rate control systems that are controlled by electrical switch closures that provide very little kinesthetic feedback and even that must be mentally translated from which button is pushed and for how long into which manipulator component is moved and in what direction. It is evident how two laboratory studies, alike in all other ways but employing such different manipulators, could yield vastly different results. The matter is complicated further when one considers the possible interactions that might occur between such differences in kinesthetic feedback and other variables affecting performance. If, for example, there was the opportunity for learning through repeated trials with highly visible, familiar objects, learning would occur much more rapidly with the exoskeletal system. If visual information were then reduced by, say, restricted resolution bandwidth or degraded visibility, performance could probably be maintained at a high level using the exoskeletal system (but not the switch system) as a result of differential kinesthetic feedback. The differential feedback provided by manipulators of different designs probably explains a number of the contradictory findings that appear in the literature.

The Nature and Effect of Learning Acquired by the Operator. The pervasiveness of learning effects in studies of remote viewing systems can readily be seen in the literature review reported by Pepper and Cole (1978) and their subsequent analysis of non-visual performance factors. Their own results show continued improvement in performance on a manipulator task over five consecutive days with 100 trials per day. Learning effects are nearly always present in studies of operator performance because our methodologies require repeated trials in order to produce reliable performance data. Two types of learning can occur in remote operator tasks: (a) perceptual learning which is involved in all aspects of the tasks that are guided by sensory input and consists of learning to attend to and discriminate the significant stimuli in the array, and (b) perceptual-motor learning which is involved in manipulator performance. Relatively little is known about the former, but perceptual-motor learning has been extensively studied and the effects of practice, fatigue, reward, feedback, etc., have been determined. As was mentioned in the discussion of manipulatorss, perceptual-motor learning is highly dependent on the type of manipulator used because of the differing amounts of kinesthetic feedback present.

There is no single method by which to control learning effects. The two most commonly employed designs are: (a) use unpracticed subjects and balance out experimental and control conditions across the sequence of trials, and (b) practice the subjects until their learning curve reaches asymptote before testing the relevant variables. Each method, even in relatively simple designs, has its shortcomings and the possibilities for interactive effects with other variables are almost assured (see example in the previous section on Manipulator Control). In conclusion, learning effects pose a particularly difficult design problem in both interpreting laboratory results and in generalizing these results to real life work situations. If learning effects generalize from laboratory to work site, then operator training might compensate for the performance degradation that results from bandwidth reduction.

Difficulties in Generalizing from Laboratory Results to Work Site Performance. There is very little data to permit direct comparisons of laboratory performance with work site performance. The most common approach is to attempt to duplicate as nearly as possible, in the laboratory, all conditions at the task site, the logic being that to the extent this goal is met, the results will be generalizable from laboratory to work site. However, since it is impractical to conduct validity checks, we have as the main basis of these generalizations, our reliance on this "face validity" between conditions in the laboratory and those at the job site.

Smith, et al (1979) have clearly described several of the potential sources of confounding in studies designed to compare viewing systems (i.e., type of task, visibility conditions, motor feedback, and the nature and degree of learning resulting from repeated measures research designs). These same variables also confound efforts to establish the validity of the laboratory measures used as predictors of on-site work performance.

Other Methodological Considerations. The procedures employed in reducing the bandwidth required for transmission of information would be expected to have differential effects on the various processes that constitute the human perceptual-motor system. This complex set of circumstances has important consequences for the evaluation of performance both at the work site and in the laboratory. At the work site the bandwidth reduction technique employed will interact with the perceptual-motor task demands on the operator. For example, when the operator is engaged in search, target recognition or vehicle positioning (situations that require a maximum of acuity, contrast and depth information, but where there is relatively little change in information over time) compression techniques that expand information transmission over time (e.g., frame rate reduction) would be expected to have minimal effects on the operator's performance while those that reduce acuity, contrast or depth information (e.g., gray scale reduction, resolution reduction and mono as opposed to stereo TV) would be expected to degrade performance. On the other hand, once the vehicle is positioned and the operator initiates a task that requires rapid but repetitive manipulator movements (e.g., valve turning), time delayed information would have greater effects on performance relative to the effects of reduction in acuity, contrast or depth information. This complication has been recognized, at least implicitly, by some researchers who have attempted to develop a normative operator performance curve for a fixed level of total information transmitted while employing various combinations of resolution, gray scale and frame rate reduction (see Ranadive, 1979).

The above cited consequences of the differential effects of bandwidth compression techniques on the various levels of the information processing network employed by the operator at the work site hold equally for the laboratory situation. But in the laboratory there is an additional complicating factor in that these effects could also interact with the psychophysical methods employed in their measurement. For example, acuity, as measured by manipulation of contrast grating patterns or standard clinical letter naming tests (e.g., Snellen Chart), would be maximally affected by resolution and by gray scale manipulation and very little (or perhaps might even be enhanced) by reductions in frame rate. However, if one employed exposure duration as a measure of threshold with either of these tests, frame rate would interact with the stimulus duration manipulation to confound those results. As a consequence, the measurement methods chosen must take into account the features of the particular bandwidth compression technique being tested, a practice not always observed by researchers in this area.

LITERATURE REVIEW

Image Enhancing Studies

There is extensive literature on the electro-optical factors involved in displaying conventional TV information. Meister and Sullivan (1969) and Funk, Bryant and Heckman (1972) define the many variables involved and summarize the findings of their effects on the physical features of the image display as well as their expected effects on known perceptual performance. Biberman (1973) edited and reviewed the literature on the parameters of image quality and their effects on visual perception. Pepper and Cole (1978) and Smith,

et al (1979) review and evaluate a number of research studies on the effects of multiple cameras on operator performance with special interest in the evaluation of stereoscopic vs. monoscopic display systems. A number of those studies have limited application to underwater work since they were conducted under visibility and task conditions encountered mainly in space exploration [Huggins, Malone and Shields (1973); Shields, Kirkpatrick, Malone and Huggins (1975); Grant, Meirick, Polhemus, Spencer, Swain and Tewell (1973); Tewell, Ray, Meirick and Polhemus (1974); and Crooks, Freedman and Coan (1975)]. Careful analysis of these conditions shows, however, that the essential parameters in the space program studies are quite analogous to those found in some remote underwater tasks, particularly those consisting of search and/or inspection under clear water, high contrast conditions. While the results of the NASA studies are not conclusive, they suggest that two cameras are better than one, that two cameras positioned orthogonally yield better performance than when positioned to produce stereo, and that color results in little or no advantage over black and white displays.

Of the studies reviewed which were conducted under conditions encountered in underwater applications, Chubb (1964), Pesch (1967), and Zamarin (1976) showed improvement in performance with stereo as opposed to mono TV systems, while Kama and DuMars (1964) and Hudson and Culpit (1968) did not. Pepper, Cole, Merritt, and Smith (1978) found improved performance using stereo as opposed to mono displays for both a pure perceptual task (stereoacuity) and for a perceptual-motor task utilizing a manipulator with limited force feedback.

Several studies not reported in the above reviews also support the efficacy of stereo over mono TV displays. Fugitt and Uhrich (1973) report improved time and error scores on a stereoacuity task when using a one camera stereo system that produces disparity images by means of a mirror arrangement. Although lacking data, the authors argue for the potential enhancement that would result from the use of color and head-coupled television.

Bertsche, et al (1978), in an extensive test of the Work Systems Package (WSP) on underwater salvage and repair tasks, employed two cameras, one which provided a close-up view and the other a wide angle view and both could be moved in pan and tilt. Performance was degraded when either camera was used alone and operators reported that their past experience with the task and the WSP was the crucial factor in maintaining their performance when only one camera view was available.

Wernli (1978) compared performance on a Peg-in-hole (PIH) manipulator task under direct view, stereo view, or a two-camera monocular view using two types of manipulator control: (a) electrical switches providing no kinesthetic feedback, and (b) analog providing kinesthetic feedback. The authors conclude, based on time and error scores as well as operators' verbal reports, that analog control and stereo view provide the best viewing-manipulator combination, but that an additional monocular camera view can be very advantageous in eliminating blind spots and as an extra assurance of proper positioning. While manipulator control by means of switches results in longer completion time and more error, it can be useful in reducing operator fatigue where the task requires accurate position keeping

or repetitive motions. Wernli's study provides a good example of the complex interaction of viewing system and manipulator feedback. Smith, et al (1979) tested stereo vs. mono viewing systems for two tasks that contained either little visual complexity, low magnitude in the depth plane and minimum requirement for scene interpretation (PIH task) or increased degrees of all three of those factors [Messenger Line Feeding (MLF) task]. These tasks were performed under three visibility conditions using a direct linkage, force-controlled manipulator that provided visual as well as force and arm-hand position kinesthetic feedback. Performance using the stereo viewing system was superior in all cases with the degree of superiority increasing with degree of visual complexity and with decreased visibility.

In summary, the evidence is quite strong that any feature of the viewing system that increases the visual information available to the operator will enhance performance. Whether this increase is brought about by the addition of a second camera that provides another monocular view or one that provides stereoscopic depth information, the degree to which this is true will depend on the extent to which task performance is dependent on stereo, as opposed to monocular depth cues and on visual feedback alone, as opposed to kinesthetic, tactile and possibly even the auditory feedback that accompanies some types of manipulator tasks. While a second monocular view can increase information considerably, stereo has the additional advantage of (a) improving visual acuity by reducing the visual noise, (b) being less affected than monocular cues by low visibility, (c) being able to look around large particles suspended in turbid water which occlude two-dimensional views, and (d) providing a slightly wider field of view (Smith, et al. 1979; Holman, 1979).

Image Degrading Studies – Bandwidth Compression

Bandwidth compression/reduction techniques tend to reduce the requirements on the information transmission link at the cost of reduction in information available to the operator. There is extensive literature on the development of hardware to accomplish the transformation of resolution (pixel/frame), gray scale and frame rate (for example, the proceedings of SPIE [Tescher, 1975] and the technical reports sponsored by ARPA over the past 10 years). This review will not report on those projects, but instead will be directed toward work that evaluates the effects of bandwidth reduction on operator perceptual and motor performance, especially as it relates to the operation of remote undersea work vehicles.

Meister and Sullivan (1969) provide definitions of terms and summaries of research relative to bandwidth features of TV displays. They also provide normative values for various bandwidth manipulations relative to their effects on perception (e.g., minimum visual angle and number of TV lines necessary to recognize numbers, letters and geometric forms, minimum frame rate necessary to perceive continuous motion, etc.).

The early and most extensive work on bandwidth compression as it relates to human performance was done on problems relevant to the Remote Piloted Vehicle (RPV) program. Only recently has there been work on bandwidth compression relative to undersea work vehicles. The RPV model is, of course, vastly different from that of undersea recovery/repair work (e.g., the air-to-ground transmission link: the remote pilot's tasks are restricted to piloting, navigation and detecting targets), but there is enough similarity, especially when the undersea operator's task involves piloting of the vehicle, search and inspection, to make a review of that literature productive.

Levine, Jauer and Kozlowski (1970) found that decreasing the number of TV lines contained in a target (resolution) and decreasing the signal-to-noise ratio result in lower target detection rates. Erikson and Hemingway (1970) measured recognition of geometric symbols and pictures of military vehicles under direct view and TV view with number of scan lines and image size varied. Performance was degraded as number of scan lines decreased. For symbols, the product of size and number of scan lines was constant whereas vehicle recognition required a minimum of 10 scan lines per target, subtending at least 14 min of arc. Craig (1974), using simulated air search scenes to study the detection of vehicle targets, found no decrease in target detection down to seven scan lines per target. Herschberger and Vanderkolk (1976) tested nine bandwidth reduction systems that could produce reductions to .94 f/sec of frame rate, resolution of 256 x 256 pixels and 1.0 bit of gray scale/pixel. They found no loss in performance for gray scale reductions at 1.5 bits or above or for frame rate reduction to 15 f/sec. Kriefeldt, Ball and Tisue (1976) tested 94 pilots and air traffic controllers for target detection under various bandwidth reduction techniques. They concluded that acceptable target detection could be achieved under markedly reduced bandwidth.

In a study reported in the ARPA 1977 annual technical report, Fogel, Mount, Skoglund and Walsh (1977) report no loss in target recognition performance using a time compression technique that varied picture display from present time to 7/60 sec delay. Fisher (1977) reduced bandwidth by developing a TV camera lens that simulated the human eye's feature of decreased acuity from the fovea to the periphery. The operator controls the direction of the camera by use of a helmet-mounted tracker. Fisher reported that target tracking performance was very good and that the wide field, while using relatively little bandwidth, was useful in maintaining operator orientation.

The study most relevant to the objective of this paper is that of Ranadive (1979) who studied the effects of bandwidth reductions in resolution, frame rate and gray scale under conditions analogous to undersea teleoperation. Using a single camera, black and white TV display, whose base line bandwidth levels were 128 x 128 pixels/frame, four bits of gray scale/pixel and 28 frames/sec, Ranadive tested performance levels on two teleoperator tasks under five levels of resolution, four levels of gray scale and nine frame rates. He tested two subjects who were highly practiced in order to reduce learning effects, and who utilized a master slave manipulator with six degrees of freedom, plus grasp, and for which the force reflection feature was disconnected in order to "limit feedback" to the vision mode. The Take-Off-Nut (TON) task required the operator to locate a nut on a bolt, grasp and turn 180° with the manipulator, pull back on the nut to test if it was off the threads, and then release, regrasp and turn the nut again. This operation was repeated until the nut was removed. The second task, named 1-2-3 task, utilized a rectangular board oriented in the horizontal plane with three small, widely separated square areas delineated by pencil or pen lines which served as "target" areas. Critical details of this apparatus were not provided by the author. The operator's task was to grasp a cork located in the middle of the board and to move it to one of the three square target areas where the grasp was released. A trial consisted of a series of nine such placements of the cork in one of the three target boxes in some predetermined order. Time to completion was the performance measure used on both tasks. Under base line conditions, average time of completion was 28 seconds for both subjects for both tasks.

Operator performance was found to be remarkably resistant to bandwidth reduction under these task conditions. With two parameters held at base line levels, overall performance on the two tasks combined was only reduced to 66 percent when frame rate was reduced to 3 f/sec; to 86 percent when resolution was reduced to 64 x 64 pixels; and to 74 percent when gray scale was reduced to 1 bit. Ranadive also assessed various combinations of resolution, gray scale and frame rate that would give constant performance or constant information transmission rates, the ultimate purpose being to allow the operator to select the combinations that would maximize performance as task demands change.

Summary and Conclusions

In summary, studies of the effects of bandwidth reduction on operator performance suggest that human perceptual processing systems are quite resistant to information loss. Ranadive (p. 124) concludes " . . . that human operators can (much to their own disbelief) perform fairly complicated tasks familiar to them with a coarse, intermittent, digitized picture requiring as little as 50,000 bits/second." But before designing viewing systems for remote underwater vehicles based on these findings, one should first consider possible limits in generalizing from these results to on-site work performance.

An analysis of the TON task suggests that the demands on the visual processing system are very minimal when it is considered that the operator was highly familiar with all features of the scene, that he was highly practiced in performing a relatively simple task under conditions of high target contrast, and that his learning experience, while it lacked force feedback information, included kinesthetic feedback. In conclusion, the effects of bandwidth reduction on operator performance should be tested under the full range of task, visibility and learning conditions that would be encountered in underwater missions.

RESEARCH PLAN

RATIONALE

One of the main objectives of this report is to develop a set of experiments to determine the effects of bandwidth reduction techniques on operator performance at the work site. A review of studies designed to assess the effects of enhanced image quality on remote operator performance shows contradictory results. Results from studies that investigated bandwidth reduction techniques, while suggesting that performance is relatively unaffected by even extreme reductions in perceptual information, appear to have limited generality. A literature review detailed the problems posed by the potential main and interactive effects of such variables as task visibility, manipulator type, learning and sensory feedback. The following research plan is designed to test the effects of three bandwidth reduction variables singly, and in combination, on operator performance under conditions that will permit the determination of their effects in interaction with the variables listed above. Such research will provide evidence regarding the particular perceptual or perceptual-motor process that is affected by bandwidth manipulation under conditions that would be expected to generalize to work site missions.

The objectives of the research plan will be met in a series of studies that will emphasize:

a. testing practiced subjects in repeated measures designs at four levels of each of three bandwidth parameters.

b. control and manipulation, where possible, of the variables revealed in the above literature search.

c. testing the basic visual perceptual components (as opposed to the perceptual-motor components) that underlie the more complex interactions involved in performing work site tasks. (Study 1)

d. testing the basic perceptual-motor responses that underlie work site performance as determined by an analysis of undersea missions (Bertsche, et al. 1978) and their further analysis into perceptual-motor components (Smith, et al. 1979). (Study 2)

e. testing these same subjects under combinations of levels of the three bandwidth parameters where the subject selects the optimal combination of the three within a constant level of information bits. (Study 3)

METHODS

Study 1: Perceptual Tasks

The purpose of this study is to determine the effects of bandwidth compression techniques on basic visual processes independent of perceptual-motor system (e.g., force feedback, kinesthetic feedback, and visual feedback of subject-induced movement) that are present in manipulator studies.

Visual processes to be tested are:

(1) Visual Acuity — smallest details that can be resolved in the horizontal plane.

(2) Stereoacuity -- smallest displacement in the depth plane that can be resolved.

(3) Pattern Recognition — percent correct recognition of alpha-numeric, geometric symbols and target objects.

Results of Study 1 would be applicable to underwater work site tasks that involve initial orientation of the vehicle in the work area, search for the work site, recognition of target objects and final positioning of the vehicle in readiness to perform recovery/repair tasks. These results will provide evidence regarding the locus of effect in the information network of the bandwidth reductions.

Subjects: Four subjects who have been clinically tested for normal visual capacity and who are highly practiced in making perceptual observations will be used in all three experiments.

Repeated measures designs will be used throughout. Learning effects will be assessed but practice trials and elimination of feedback will be used in an attempt to keep learning effects at a minimum.

Stimulus materials for the visual acuity study will consist of photographic reproductions of black and white grating patterns that vary systematically in stripe width. Patterns will be presented in four orientations: 0° (vertical) 45°, 90° (horizontal) and 135°. The subjects' task is to discriminate the presence of the grating pattern and report its correct orientation. Percent correct responses will be plotted against visual angle subtended by the stripes in the grating patterns under conditions of direct view and TV view when the TV utilizes commercial bandwidth capacity. The direct view condition is to provide a base line for determining information loss due to the TV system under optional bandwidth conditions and the latter condition is to provide a base line to assess information loss due to various bandwidth compression techniques. Detection thresholds will than be determined for each of four levels of frame rate, resolution and gray scale.

Stimulus materials for depth acuity determination will be the Howard-Dolman Apparatus used by Smith, et al (1979), to test stereo vs. conventional displays under a number of task and learning conditions. The apparatus consists of two vertically displayed rods of which one can be moved fore or aft in the depth plane relative to the stationary rod. The operator's task is to determine the point at which the movable rod is in the same depth plane relative to the stationary rod. A repeated measures design similar to that described for visual acuity will be employed with base line threshold established for natural view and standard bandwidth conditions before determinations are made for each of four levels of frame rate, resolution and gray scale.

Stimulus materials for pattern recognition studies will be similar to those utilized by Erickson and Hemingway (1970) in their study of image identification on television. Erickson measured detection thresholds for geometric symbols and military vehicles when viewed directly or on TV as a function of number of scan lines per image and angular subtense against three backgrounds that were expected to interact differentially with the above variable. Similar stimulus materials will be used to determine pattern recognition thresholds under direct view and under commercial quality TV view, after which recognition thresholds will be measured for four levels each of frame rate, resolution and gray scale.

Study 2: Perceptual-Motor Tasks

The purpose of this study is to determine the effects of bandwidth compression techniques on operator performance of manipulation tasks that model as nearly as possible underwater work site recovery/repair tasks.

Selection of tasks was guided, first by the work of Bertsche, et al (1978), who selected 14 tasks to represent the entire tool work capability of the manipulator and tool suite of the Work Systems Package (WSP). These 14 tasks were then analyzed into 23 behavior motions and subtasks of which a subset of four, taken in proper sequence, could be proscribed for each of the 14 tasks. These laboratory procedures were validated against work site recovery/repair operations by means of utilizing laboratory measures of time of completion of various tasks and subtasks to predict work site task times and mission times. These predictors agreed quite well with work site times obtained from previous sea trials and recovery times.

Task selection was further guided by the work of Smith, et al (1979), who analyzed undersea manipulator tasks into three general categories based on similarities in their major perceptual and motor components. The PIH task, labeled a category 1 task, consists of perceptual-motor components that are common to five of the 14 major tasks listed by Bertsche. The MLF task developed by Smith, et al, and labeled a category 2 task, contains perceptual-motor components that are found in at least six of Bertsche's tasks. Finally, we were guided by the recent work of Ranadive (1979) who assessed the effects of bandwidth compression on two laboratory manipulator tasks. One of his tasks has many perceptual-motor components in common with Smith's MLF task but, unfortunately, was limited by the fineness of details of the critical elements on the work surface. As a result, even small bandwidth reductions in resolution and/or gray scale rendered the task impossible to accomplish. His second task (TON), however, is similar to our PIH task with the additional perceptual-motor requirements associated with successive rotary motions interspersed with releasing and regrasping movements.

These three tasks then provide a fairly broad sample of the perceptual-motor requirements from an extensive list of actual work site recovery/repair tasks for which at least some data exist regarding their generalizability to undersea work site performance and for which extensive data already exist on laboratory performance under a number of viewing system, visibility, manipulator and operator conditions, including learning.

Study 2a. The PIH task as described in Smith will be the first manipulator task tested. Procedures and methods will be similar to those reported for practiced subjects. Four highly practiced subjects will be tested under direct view and under a commercial bandwidth TV view to establish base lines for comparison of bandwidth compression techniques. Subjects will then be tested on four levels each of reductions in frame rate, resolution and gray scale. In order to insure that the task is visually guided on each trial, the rotational position of the taskboard and its angled elevation will be changed between trials. Time of task completion will be recorded.

Study 2b. A TON apparatus and general procedures similar to those reported by Ranadive (1979) will be used. In order to insure that the task is visually guided, the threaded bolt will be mounted on the PIH board to permit change in position of the critical features of the task board between trials. Testing conditions for direct and commercial TV views and levels of bandwidth compression will be the same as in Study 2a. Time of task completion will be recorded.

Study 2c. The MLF task apparatus and general procedures similar to those reported by Smith, et al (1979) will be employed and the same testing conditions as those in the above two experiments will be repeated.

Study 3: Subject Control of Bandwidth Parameters

Following the analysis of the data from Study 2, minimum levels of information bits will be determined for each of the PIH, TON and MLF tasks. Those tasks will then be repeated with the subject setting the "best combination" of resolution, gray scale and frame rate to maximize performance at a fixed level of information.

Data Analysis

The results of each of the experiments in Study 1 and Study 2 will be analyzed by means of a repeated measures analysis of variance to determine the significance of main and interaction effects. Tests of trend and of differences between individual means will be performed as appropriate according to Winer (1971).

The results of Study 3 will be analyzed in terms of the percent contribution of each of the three bandwidth parameters as they relate to operator performance.

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